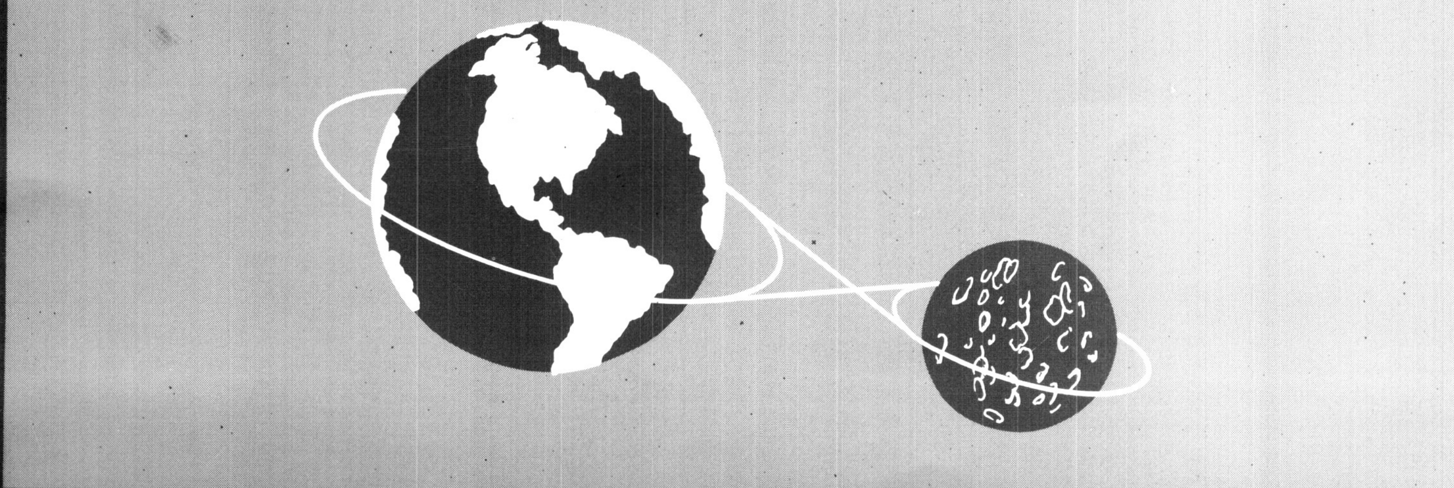
File under LUNAR BASES
7N-12-TM

LALP - 84 - 43

sponsored by the
National Aeronautics and Space Administration

hosted by the
Los Alamos National Laboratory branch of the
Institute of Geophysics and Planetary Physics
of the University of California



Report of The Lunar Base Working Group

April 23-27, 1984

LALP-84-43

Issued: August 1984

Report of The Lunar Base Working Group

April 23-27, 1984

Compiled by

Michael B. Duke*
Wendell W. Mendell*
Paul W. Keaton**

Special Assistance
Bevan French†

Workshop Director
Michael B. Duke

*Code SN, NASA Johnson Space Center, Houston, TX 77058.
**Physics Division, Los Alamos National Laboratory, Box 1663, Los Alamos, NM 87545.
†Code EL4, NASA Headquarters, Washington, DC 20546.

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

CONTENTS

OVERVIEW

Background

As a result of the operational Space Shuttle and the commitment to build a permanent Space Station in the 1990s, much of the enabling technology for a permanently manned lunar base will exist by the end of this century. Such a base can provide a major national goal after the Space Station.

The cost of establishing a permanent base on the Moon can be funded within NASA's budget if NASA continues to receive the same fraction of our nation's wealth as it has in the past [less than 0.4% of the U.S. gross national product (GNP) over the last 25 years].

Although a decision to establish a lunar base may lie several years in the future, certain activities need to be initiated now to provide the data base necessary for such a decision. To study the opportunities and general problems associated with a lunar base, a meeting of about 50 people convened at the Los Alamos, New Mexico, branch of the University of California's Institute of Geophysics and Planetary Physics from April 23 through 27, 1984.

Discussions focused on the following topics: (1) use of the Moon for scientific experiments, (2) potential uses of lunar resources to support space activities on and off the Moon, (3) human factors in a lunar base, (4) technology requirements for a lunar base, and (5) political and social implications of a lunar base.

The workshop did not consider detailed plans for development of a lunar base, but focused instead on more general issues. It was assumed that any lunar base program will be evolutionary and pass through several stages: (1) a preliminary exploration of the Moon for mapping, surface exploration, and site selection; (2) a scientific and technology research outpost with some options for industrial pilot plants; (3) a base with a permanent manned presence and additional pilot plants; and (4) a fully operational base that moves toward self-sufficiency and independence from Earth.

Toward the end of the workshop, the attendees developed a "white paper" stating, on a single sheet of paper, the recommendations of the workshop and the significance of a lunar base program in our nation's future. This concise statement is an independent document to be separately and widely distributed. The white paper, in an edited form agreed to by nearly all participants, is reproduced in Appendix A.

Workshop Conclusions

- **A permanent lunar base will make possible unique and important scientific experiments in a wide range of fields.** Planetary science, astronomy and astrophysics, space plasma physics, life sciences, fundamental physics, materials processing, and engineering are examples.
- **Permanent access to lunar materials creates the potential for obtaining useful industrial products.** Because transportation costs are the key driver in establishing a lunar base, early industrial development will focus on products, such

as bulk lunar material for radiation shielding and oxygen for rocket fuel, that assist the Space Transportation System. Later developments will emphasize the use of lunar material to support construction and other activities on the base itself, tending toward diversification, increased sophistication in processing, and self-sufficiency from Earth.

- **Establishment of a permanent lunar base will bring about a major change in our space activities and also in our human development.** A lunar base will require new techniques to support human activities and human societies under unique conditions. Special problems include human operations, shelter technology, life-support systems, and health and medicine under lunar conditions.
- **A permanent lunar base will need new technologies, none of which appears impossible or requires future scientific breakthroughs.** The evolutionary lunar base model requires continuing development in such areas as space transportation, surface mobility, habitations, life support, and power.
- **A permanent lunar base will involve important societal and policy aspects.** A lunar base will generate significant changes in many of our current institutions, such as international space law, international cooperation in space, and private enterprise in space.
- **The cost of a permanent lunar base is not prohibitive.** Because much of the needed technology will already be available, the cost is estimated roughly as comparable to the Apollo Program, which amounted to less than 0.3% of the U.S. GNP from 1962 to 1972. Since then, even after correcting for inflation, the U.S. GNP has more than doubled. Furthermore, it is expected that the evolutionary establishment of a permanent lunar base will last twice as long as the Apollo Program. Therefore, a lunar base program will cost less than 0.1% of the U.S. GNP.

Workshop Recommendations

- A permanent lunar base should be adopted by NASA as a long-term goal for the early 21st century.
- This long-term goal requires near-term planning. Although the commitment to build a lunar base lies perhaps 10 years in the future, significant studies of scientific, technological, economic, and societal factors should be started now to provide the necessary data for an informed decision in the future.
- Studies of the uses and implications of a lunar base for scientific investigations should be carried out soon.
- Several areas of critical technology should be targeted immediately for NASA research. These include

  Areas currently under study, which are generally relevant to a lunar base: space transportation, power, and long-term habitation. These studies should be modified to include lunar base possibilities and needs.

  Areas not currently under study, but which are critical to a lunar base, include the use of lunar materials, potential extraction of lunar oxygen, life support under lunar conditions, and the substitution of lunar materials for terrestrial materials in space construction. These studies should be initiated in the near future.
- Requirements for a lunar base should be specifically considered during the development of near-space transportation systems, especially in the development and establishment of the Space Station.
- Mechanisms should be established to enable continued dialogue and consideration of the lunar base. The planned public symposium (Washington, D.C., October 29-31, 1984) is an important initial step in this process.

Report of
THE LUNAR BASE WORKING GROUP
April 23-27, 1984

INTRODUCTION

> . . .it is inevitable that human habitation will eventually extend beyond the confines of the Earth in many ways and on a scale far larger than is currently envisioned.
>
> --NASA Advisory Council Study of Mission of NASA, October 12, 1983.

It is also inevitable that the extension of civilization beyond Earth will include a permanent settlement on the Moon. The only real questions concerning a lunar base are, "When?" and "How?" Examination of the American civilian space program suggests surprising answers to these questions. Several changes have occurred in the United States that now make a Moon-base project feasible within the next two decades. These include the

- development of an operational Space Shuttle, which makes manned space flight again possible after a long hiatus in the United States program;
- reversal of the economic recession of the early 1980s, which has created a more favorable climate for considering long-term major national projects again;
- targeting of space development as a high-technology investment by the private sector, in a drive toward commercializing space;
- public acceptance of the federal space effort, which is more favorable now than at any other time in our history; and
- Presidential support of a Space Station program, which would provide both a platform in space and the start of a reusable transportation system beyond low Earth orbit.

The manned Space Station will be established in low Earth orbit before the end of this century. A space-based orbital transfer vehicle (OTV) will be designed to deliver payloads from the station to geosynchronous orbit as well as to destinations beyond. The Space Shuttle, the Space Station, and the OTV will constitute the rudiments of a space transportation system capable of placing payloads routinely in lunar orbit (see Appendix A for the statement of the Lunar Base Working Group and Appendix B for a list of abbreviations, acronyms, and notes).

Historically, the Moon has been an important objective for each new wave of technical capability by the space-faring nations. It is entirely reasonable for us to anticipate that the establishment of permanent presence in space will extend to a manned outpost on the lunar surface once the enabling technology is in place. The principal criticism of a near-term manned lunar base is not of the technical feasibility but the supposed large cost for such a project. A conservative cost analysis based on past space funding trends suggests, however, that presently projected expenditures for the next two decades can accommodate a manned lunar program of significant scope.

Because concepts for future space transportation systems are now being formed within NASA, it is appropriate to ask some fundamental questions about a permanent human habitation on the Moon. Are there compelling scientific, economic, or cultural reasons for placing humans on the Moon? How does a manned lunar base fit into the context of other possible space activities in the first part of the twenty-first century? What are the technology challenges and risks? Given that the first permanent settlement on another planet will mark a historical occasion, what are the implications for our society and for the political structure of the world?

To address these questions, the Lunar Base Workshop formed three groups* to consider various uses of the Moon, a fourth group to consider technology issues, and a fifth to discuss social, political, and economic aspects of the project. Uses of the Moon were emphasized because such issues will tend to drive the research and development in any eventual NASA program plan. Each of the working groups is described briefly below.

Uses of the Moon--Scientific. In any scenario of lunar activity, much of the effort at the lunar surface is devoted to the expansion of scientific knowledge. Priority should go to investigations for which the Moon is uniquely suited or which are particularly easy to do on the Moon. One or two members from each major discipline in the physical sciences addressed the questions of appropriate lunar-based research.

Uses of the Moon--Industrial. Using lunar resources adds an important economic element to a manned base program. Because transportation costs will constrain establishing the base more than any other factor, the first industrial processes probably will be aimed at making lunar materials available to the space transportation system. The production of oxygen for rocket propellant is an obvious example, but other examples include using bulk lunar material ("soil") for radiation shielding and using lunar-derived materials for the ablative component of aerobraking freighters returning to the Space Station from the Moon. All industrial processes seem to require surface mining and most involve thermochemical processing. Discussion emphasized chemical engineering, mining, and bulk processing.

Uses of the Moon for Self-Sufficiency. Severing the umbilicus between Moon and Earth is an event that will transform the lunar settlement from a technological feat to a cultural watershed. When humans first return to the Moon, their abilities to operate in the environment will be awkward and artificial. In some sense, they will be worse off than aborigines because they will not be creatures adapted to that environment. Using tools at first imported, they must construct whatever they need to deal with the lunar environment and to live there with minimal resupply. The whole spectrum of biological processes associated with the growth of food and closed ecological life-support systems (CELSSs) is important, but we must also determine what tools should be built on the Moon and what tools should be brought from Earth to develop the lunar technological infrastructure. This group's discussions emphasized the human factors in lunar base design.

Technological Feasibility of a Lunar Base. At JSC an engineering task group recently prepared information about the feasibility of a lunar base and formulated projections of existing technology to the year 2000. A working group reviewed that document and identified key technologies that must be developed by NASA for a return to the Moon. In addition, outputs from the three groups described above were monitored to identify technology development needed to satisfy the integrated requirements generated by the groups.

Context of Lunar Occupation in Society. The political, social, and economic context for the declaration and accomplishment of a return to the Moon will unquestionably influence the style and timing of the project. Conversely, the habitation of the Moon will affect geopolitical relationships. This group considered the societal implications of the initiative, and they are discussed in this report.

* See Appendix C for workshop organization and structure. (Appendix D lists technology issues and opportunities; Appendix E, workshop attendees and their affiliations.)

WHY RETURN TO THE MOON?

In the early 1990s, a low Earth-orbit Space Station will place American men and women in space permanently for the first time and will irreversibly alter the nature of the manned space program. No longer will isolated, temporary sorties outward catch the public imagination as did the Apollo mission and as do individual shuttle launches today. Manned explorations of space will become more continuous and territorial as astronauts "occupy" rather than "visit." We can draw a clear analogy here with the early days of the American space program. Alan Shepard touched space, but John Glenn actually attained orbit. After Glenn's flight, suborbital flights were never again considered as program goals. Similarly, the major manned programs beyond the Space Station will no longer focus on short visits to space.

For the post-Space-Station era, a number of major space projects have been suggested. These include more elaborate activities in Earth orbit, space stations in other low orbits, a manned platform at geosynchronous orbit, or the construction of large solar power satellites. Preliminary analyses of such large-scale space activities have established that their dominant costs are generated by the need to lift great masses of material from Earth to orbit, and it has been suggested that using materials obtained from the Moon or from Earth-crossing asteroids could alleviate these transportation costs. These suggestions have not generally been examined in detail because they imply the existence of industrial activities on the Moon or elsewhere.

Two other future goals commonly mentioned are a manned lunar base and the manned exploration of Mars. Either of these two projects represents a philosophical jump beyond Earth-orbit activities. The first human habitation on another planetary body will mark a cultural watershed. The idea stirs the long-term expectations and aspirations of many people.

With a lunar base, unique long-term scientific investigations can be conducted on the lunar surface. The most obvious activities are the direct study of the Moon and the exploration of more general problems in planetary science. Important experiments in other disciplines are also made possible by the unusual lunar environment. Several excellent examples are discussed later in this report.

Lunar resources can potentially support large-scale space activities by providing rocket propellant and construction materials. Exploitation of lunar resources can occur only with development of a lunar operational capability which, in turn, can grow only as an evolutionary part of the general space transportation capability. Thus, the whole system must be carefully thought out to be self-consistent and mutually supportive.

Scientific discovery and grand exploitation schemes, by themselves, will never justify a manned lunar base. Such an activity must also support the national strategic interest in space. In the past, the space program has been an effective vehicle for instilling national pride, promoting national prestige, and stimulating the technology base of American industry. Today, another element of space policy is the *maintenance of a strong and viable civilian presence in space.*

Any serious reconsideration of manned planetary exploration must take place in light of today's economic and political realities. The space program has become part of a complex, changing society, and space activities are no longer sheltered by the "Kennedy mandate" that generated the Apollo Program. Choices in national space policy will affect international relations, national security, private investment in space, and the growth of the national technology base. A manned lunar base project is consistent with today's social, economic, technological, and political realities.

International cooperation has always been a goal of the American space policy. The Apollo-Soyuz Test Project was a visible example of bilateral U.S./U.S.S.R. cooperation. Close interactions with Western countries are now being discussed for the Space Station project. Bolder projects leading to settlement of the Moon and Mars will inevitably raise new and intriguing geopolitical issues and create new opportunities for innovative modes of interaction between nations.

Why return to the Moon? To summarize, the Space Station will change the way our society views space. Subsequently, major U.S. goals will focus on occupying rather than visiting space. Among the possible alternative goals that can follow the Space Station, a permanent base on the Moon offers the most robust combination of factors that will foster steady long-term growth for our nation's space future. These factors include

- lunar-derived oxygen that can feed back into the transportation system and make it less expensive;
- bulk lunar resources that will provide useful materials for constructing shelters and enhancing other large-scale space activities;
- enabling technologies that will exist by the time lunar base construction begins, thereby allowing a smooth transition from the objectives of a Space Station to the goals of establishing a lunar base;
- basic and applied scientific investigations that range from comparative planetology and stable-platform astronomical observations to utilizing the unique lunar environment for conducting experiments to understand the fundamental laws of nature; and
- grand aspirations that will establish the first human society on another planet, marking a cultural watershed of sufficient magnitude to inspire broad public support and international respect.

USES OF THE MOON

Scientific

A permanent lunar base offers the opportunity to study the Moon in much greater detail than has ever been possible. It also allows us to use the unique environment of the Moon as a platform for astronomical, solar, and space plasma observations. A brief description of the lunar environment follows along with a discussion of several areas of scientific research that could be carried out on the Moon.

The Lunar Environment

Unique environmental characteristics of the lunar surface include low gravity (one-sixth that of Earth), high vacuum (10^{-12} torr), seismic stability, low temperature at the poles (50 to 80°K), and low radio noise on the far side. The surface and near-surface charged plasma and magnetic and electric field charcteristics of the Moon are controlled by a combination of lunar surface effects and external plasma environment, with the Moon spending three-quarters of the time in the solar wind and one-quarter in the Earth's magnetotail. Within a few meters of the dayside surface, the electric field is dominated by the photoelectron sheath; the field has a magnitude of roughly 20 volts per meter on the dayside.

The magnetic fields near the lunar surface are spatially variable; small-scale magnetic fields associated with permanent lunar surface features may reach 100 gammas. These permanent surface fields may locally dominate the solar wind field of approximately 5 to 10 gammas or the magnetotail field of 50 gammas. The tenuous lunar atmosphere consists of solar wind gases (mostly hydrogen, helium, and neon) and minor amounts of other gases (such as argon) apparently outgassed from the lunar interior.

The gamma-ray and neutrino backgrounds are low in relation to those of the Earth. Primary cosmic-ray intensities are more uniform and constant than at the Earth. Penetrating particle radiation is highly variable, with solar-flare protons representing the most hazardous component at extremely high flux levels.

Other relevant physical parameters at the lunar surface include a low rotation rate (2-week days and nights), large thermal gradients from sunlight to shadow, and the hypervelocity impact by small cosmic particles (micrometeroids).

Investigations

History of the Moon and Planets. Despite the wealth of information provided about the Moon by the Apollo Program, there are still many unanswered questions. We do not know exactly how the Moon formed, nor how it evolved. These gaps in our knowledge have broad implications for our understanding the histories of other planets, including the Earth. To progress toward better understanding, we must answer other pressing questions. What is the interior structure of the Moon? How large is its metal core, if any? What is the full range of rock types present, and how are they distributed across the lunar surface? What is the nature of the oldest lunar rocks? What are the youngest rocks like, and how old are they? What is the Moon's bulk composition? Are volatile elements more abundant in the Moon at depth than in the crust? Further study of lunar samples collected by Apollo will bring some tentative answers, but firm conclusions can come only from a return to the Moon for detailed *in situ* study. In the following paragraphs, we provide only a glimpse of the extensive research concerning the Moon's origin and history that can be carried out from a manned lunar base.

As we explore the lunar interior, we gain basic data about the Moon's bulk composition and melting history. To characterize the lunar interior more effectively, an array of seismic detectors, as many as 30, should be uniformly distributed over the lunar globe. This network must operate continuously for many years to detect and characterize naturally occurring internal moonquakes and to record travel times of the stress waves produced by large meteorite impacts. We can investigate the existence of a lunar core and the presence of large-scale inhomogeneities within the Moon. The presence or absence of even a small core is crucial to answering such questions as whether the inside of the Moon ever passed through a molten phase or whether the Moon retains any volatile components deep in its interior. Heat flow measurements at the lunar surface were made at only two sites during the Apollo program; these measurements should be made at many more places to enable the determination of the amount and distribution of radioactive elements within the Moon. Radioactive elements are distributed nonuniformly over the lunar surface, but we do not know whether this inhomogeneity extends to depth. Measurement of the heat flow can provide information on the distribution of radioactivity laterally and with depth; this information is crucial to models of lunar structure, bulk composition, and history.

Development of a full understanding of the origin and evolution of the Moon's crust has been hampered by the limited number of samples collected by Apollo over a small area of the Moon. A lunar base can provide the opportunity for detailed studies in all types of terrain. These investigations can be designed to determine the ages of the oldest and youngest rocks, the style of implacement of the earliest crustal units, the nature of rocks brought up from depth by large impacts, and the manner in which impacts hurl material across the lunar surface. Such studies require the capability to map and sample the lunar surface along traverses hundreds of kilometers long and to scale crater walls and central uplifts.

The nature and distribution of volatile elements and compounds in the Moon are important. In addition to the desirability of searching for the existence of any water on the Moon, the other volatile elements known to be present in the Moon in small quantities have major implications for our understanding lunar origin, composition, structure, and history. The rocks and soil exposed at the lunar surface are greatly depleted in volatiles compared with the Earth, which implies that their source materials passed through an extensive outgassing stage. However, high concentrations of some volatile elements (lead, zinc, cadmium, and chlorine) are found deposited on surfaces of glass droplets formed during volcanic explosions and collected at the Apollo 11, 15, and 17 sites. A primordial (not formed by radioactive decay of uranium and thorium) isotope of lead, lead-204, is also abundant in these deposits. These data indicate that at least some portions of the lunar interior could provide volatiles, which would then be carried to the surface by volcanic eruptions. Extending these observations to other samples of lunar volcanic rocks, particularly those from known depths, is fundamental to determining such major questions as the extent to which the Moon was molten when it formed and whether it contains any significant amount of volatiles at depth today.

The Moon is also a useful detector that can give valuable information about solar and cosmic-ray history. Detailed study of solar wind and solar-flare particles trapped in the lunar surface layer (regolith) can trace changes in solar activity over the past four billion years. The core samples obtained during Apollo missions contain such a record of the Sun's history. However, the lunar regolith is too complicated to be understood on the basis of a few samples. Detailed studies supported by a lunar base would include deep coring (up to 10 m), trenching, *in-situ* inspection of lunar regolith sections, and greatly expanded sampling and analysis.

Astronomy from the Moon. More astronomical observations will be made from space in the future, primarily to escape the Earth's atmospheric and ionospheric absorption and distortion. Space astronomy from the surface of the Moon offers at least three potential advantages over both ground-based and Earth-orbital observations:

- The far side of the Moon is permanently shielded from direct terrestrial radio-frequency emissions. As radio telescopes approach theoretical limiting sensitivities, this uniquely quiet lunar environment may be the only place where such instruments can be fully utilized for astronomical research and in the search for extraterrestrial intelligence (SETI).
- The Moon's surface provides a solid, seismically stable, low-gravity, and high-vacuum platform for precise interferometric and astrometric observations.
- Over at least the next few decades the Moon may offer the only permanently manned bases that lie beyond the Earth's geocorona, and which are also normally outside the Earth's radiation belts. The Moon will thus offer a variety of observational programs in an inherently low-background-radiation environment.

These advantages of the lunar environment suggest the development of two principal classes of astronomical facilities on the Moon, respectively devoted to the achievement of

- ultrahigh (microarcsecond) astrometric positional accuracy and angular resolution with interferometric arrays at microwave, infrared, and optical wavelengths and
- greatly improved sensitivity for detection of faint sources of electromagnetic radiation at all wavelengths, of charged particles (cosmic rays and solar-wind plasma), and of exotic radiations, such as neutrinos and gravitational radiation.

Astronomical observatories that might be constructed on the Moon are listed in the table. This list is meant to be illustrative rather than exhaustive.

We can now raise significant scientific questions that require the resolution and sensitivity offered by these types of lunar observatories; observations from space in the next two decades will undoubtedly add new questions to be addressed by even more capable systems.

- The current model for the central energy source in galactic nuclei and quasars involves a central black hole accreting

POSSIBLE ASTRONOMICAL OBSERVATORIES ON THE MOON

Type	Characteristics	Comments
Optical telescope	25-m aperture, UV resolution ~1 milliarcsec	Collecting area 100 times the space telescope (ST); sensitivity 104 times the ST
Optical interferometer	25-km effective aperture, 1-microarcsec resolution	
IR/Submillimeter telescope	25-m aperture, 0.1-arcsec resolution at 10 microns, helium cooled	Collecting area 2,500 times the infrared astronomical satellite (IRAS)
IR/Submillimeter interferometer	1,500- to 3,000-km baseline microarcsec resolution at 10 microns	
Very large-aperture EUV/x-ray telescope	Mirror array or coded aperture/imaging detector	Reflecting area 30 times the advanced x-ray astronomy facility (AXAF)
Solar observatory	Milliarcsec resolution	
Cosmic-ray observatory	Passive and active detectors	
Gamma observatory	Large aperture, good spectral and angular resolution	
Neutrino telescope	Large mass, complex detectors	
Gravity waves	Large interferometric detectors	

mass from surrounding stars. Critical tests of this model require microarc-second observations at radio, optical, and x-ray wavelengths.

- The availability of ultrahigh-resolution optical, infrared, and radio observations will also allow (1) detection of planets orbiting nearby stars, (2) parallax and proper motion measurements of stars over the entire galaxy, (3) fundamental improvements in the cosmic distance scale, and (4) more precise estimates of the mass density in our own galaxy, in external galaxies, and in clusters of galaxies--critical information about the "invisible" 90% of the matter in the universe.
- Very high-resolution (one milliarcsecond) studies of the solar photosphere, chromosphere, and corona, combined with precise measurements of the flux, isotopic composition, and temperature of the solar wind may well allow a definitive understanding of the basic magneto-hydrodynamic phenomena that govern stellar atmospheres.
- Understanding the evolution of the universe and of galaxies requires that primordial galaxies with large red shifts be detected and studied. Detailed study of these objects will require large-area, low-background instruments at optical, infrared, microwave, and x-ray wavelengths.
- Supernovae play a critical role in many processes that affect galactic evolution, including the formation of the heavier chemical elements, the formation of new stars, and the structure and dynamics of the interstellar medium. A full understanding of the supernova detonation process, and of the processes that form the elements, will require spectroscopic studies of supernova remnants and the observation of extragalactic supernova explosions at optical, radio, x-ray, and gamma-ray wavelengths. This will require large-aperture, low-background instruments. In addition, neutrino observations and gravity wave detections of galactic supernovae will be critical to our understanding certain aspects of the supernova explosion.
- Solar system studies will benefit from very high-sensitivity and very high-resolution observations with a 30-m-aperture optical telescope. For example, comets residing in at least the inner part of the Oort cloud (at 1,000 to 100,000 astronomical units distance) could be detected and studied.
- The study of cool objects, such as interstellar clouds and young stars still embedded in their parent clouds, requires high-resolution and high-sensitivity spectroscopic observations in the infrared and submillimeter bands. The development of large-area (10- to 30-m) cooled collectors or arrays can provide unique capabilities for studies of this type.

The nature of these astronomical investigations requires measurements over a wide range of wavelengths; consequently several complementary facilities are needed. Certain advantages can be gained from collecting these facilities at central observatories on the Moon.

Plasma Observatory. The Moon presents no large-scale obstacles to the solar wind because it lacks both a dense atmosphere and a large-scale intrinsic magnetic field. Instead, the Moon acts as an absorbing surface to the charged solar-wind plasma. Within a few meters of the surface, modification of the solar-wind electric field by the photoelectron sheath produces some perturbation to the solar wind, but above 5 to 10 m, the solar wind is essentially unperturbed by the lunar presence.

In addition to the solar-wind environment, the Moon spends about one-fourth of its orbit traversing the tail of the Earth's magnetosphere. Here the Moon is shielded from the flowing solar-wind plasma and its associated electric and magnetic fields and is, instead, exposed to the plasma and fields in the geomagnetic tail.

A large-scale lunar surface grid of plasma and field detectors would allow unique studies of the solar wind and magnetospheric tail not possible at present from single satellites. In addition, chemical releases (barium, strontium, etc.) by surface-launched sounding rockets in the upstream solar wind would allow unique studies of important plasma phenomena, such as development of micro- and macroinstabilities, anomalous ionization processes, and solar-wind sweeping effects.

Life Sciences and Ecosystem Studies. Two general goals of life science investigations in space are (1) to understand how biological mechanisms (for example, metabolism and growth) function in the space environment and (2) to develop life-support systems to ensure human safety and mobility in space.

Both goals require extensive life science investigations in the unique environment of the Moon. Studies of biological processes at 1/6 g will provide fundamental data about such mechanisms as plant growth and human physiology in space and will also identify the unique effects of low gravity (as distinct from 1 g or microgravity) on these mechanisms. With this understanding, we can develop better procedures for crew health and medical care in the lunar environment.

These studies will also provide an essential data base for the development of life-support systems suitable for long-term habitation in space. Such systems will require closed ecological processes, efficient recycling procedures, agriculture, and independence from Earth-based supplies. Such closed systems will be essential to expand long-term human habitation elsewhere in the solar system.

Other Research Opportunities on the Moon. We can describe one class of scientific investigations that will be conducted on the Moon as the pursuit of "science in space" (science under the conditions extant in space), which is to be distinguished from "space science" (the science of the phenomena of space). Most basic experiments focus on reducing the systematic errors by changing critical parameters. We seldom consider some parameters, such as the Earth's gravitational acceleration of 1 g, as a possible "variable" in experiments. Science in space is a class of investigations that can benefit from changing some of the most fundamental parameters of the Earth's environment.

New levels of chemical purity, high vacuum, low magnetic fields, reduced gravity, low neutrino backgrounds, and direct access to space suggest exciting discoveries and fundamental experiments. For example, it will be important to investigate the biological consequences of low magnetic fields. Furthermore, new frontiers in "clean chemistry" as well as materials science can be advanced in the high vacuum and low gravitational fields possible at a lunar laboratory.

As a further illustration of science in space, we consider the search that has been called "the experiment of the century" by particle physicists. The purpose of the experiment is to test theories of matter by determining the lifetime of the proton. A large mass of water, laminated iron plates, or even thin layers of processed lunar-derived material (such as cement) can be the source of protons. At present, the current sensitivity limit of proton decay measurements is about 10^{33} years. Neutrinos mimicking the proton decay are the major background problem in making this measurement on Earth, because cosmic-ray interactions with the Earth's upper atmosphere contribute significantly to the terrestrial neutrino background flux. On the Moon, however, the neutrino production rate is much smaller because there is little atmosphere. By estimating the reduction of the neutrino background, we conclude that proton decay lifetimes in the range of 10^{34} to 10^{35} years may be measurable on the Moon.

Engineering Properties of the Lunar Environment. Applied research related to the lunar surface environment needs to be undertaken in order to enhance our ability to carry out scientific and operational activities on the Moon. Previous studies of lunar materials have provided much of the information needed to design large structures for the lunar surface. From returned lunar samples, we have information on the density, shear strength, thermal conductivity, and dielectric properties of fragmental lunar surface layer (the regolith, or "lunar soil"). This layer is "gardened," that is, crushed, ground, stirred, and mixed by meteorite impacts to depths of several meters. The cohesive nature of the soil is mechanical; it is not due to vacuum welding produced by implanted gas on particle surfaces.

A number of unexplored concerns remain despite this extensive data base. These include possible effects of the extreme lunar temperature cycle on properties of the soil, such as thermal expansion; the possibility of differential settling under a sensitive structure, such as an observatory; the effects of thermal and electric field cycling on the lunar dust (and how it will adhere to critical surfaces used for observations, thermal control, or solar power); the site studies necessary for selecting stable platforms; and a simple means of location on the surface.

Environmental Factors

Most lunar scientific research activities require that the unique lunar environment be preserved. Lunar base operations might affect this environment in adverse ways, especially if industrial operations expand. For example, atmospheric pressure could increase and atmospheric composition could change, thus compromising astronomical observations. Extensive satellite communication networks might increase the very low radio-frequency background that makes the far side of the Moon an ideal place for radio telescopes. Means of monitoring and controlling lunar pollution should be studied.

The idea of designating certain areas of the Moon as scientific reserves (for example, much of the far side for radioastronomy) deserves study as well. Because it seems certain that some level of environmental degradation will occur as a result of lunar base activities, the lunar surface should be thoroughly sampled and characterized during the initial base operation. This would ensure preservation of pristine, uncontaminated, prebase lunar samples. The types, number, sites, and locations of such samples need further study as well.

Conclusions

- The lunar surface, the best location for several classes of scientific experiments, may be the only feasible location for many important experiments or observations.
- A program defining the types of scientific research on the Moon should be initiated to verify and extend current concepts.
- Monitoring and controlling changes in the lunar environment due to activities associated with a lunar base should be preplanned and carried out in conjunction with extensive sampling and characterization.
- Future scientific use of the lunar environment will require numerous technological developments. Among these are long-range surface transportation and communication systems and techniques for the construction or assembly of large instruments.

Industrial

As we migrate into space, extraterrestrial industrial development marks the beginning of an ability to sustain ourselves, materially and economically, in a new environment. Our ability to provide useful products from lunar material will critically affect the capabilities and growth rate of the lunar base. Simultaneously, such abilities can support other activities in space--for example, the production of oxygen to be used as a propellant for vehicles departing from low-earth orbit (LEO), the use of lunar dirt or metal for shielding in space, and the production of ceramic and metal products for structures in space. We already know enough about the Moon and its common materials to list potential products and to develop procedures for producing them. Such manufacturing is reasonable and feasible by the end of the century, although much near-term research is required to settle on specific processes.

Lunar Industry

A lunar base provides an excellent opportunity to develop our ability to adapt space resources to meet dwellers' needs. The first lunar base can demonstrate industrial capabilities after its initial phase by landing and operating small pilot factories to provide various materials for use on the Moon and in Earth orbit. Factories for one or two products could be established early; a larger effort could focus on research, exploration, and obtaining experience, under lunar conditions, in testing equipment and using indigenous materials. This knowledge and experience would guide the design of the next-generation factories. A carefully planned effort could hasten our capability in obtaining materials for construction and life support and in providing and transmitting power for the growth of activity on the Moon and in Earth orbit.

Potential Products and Applications

The Moon has ample supplies of silicon, iron, aluminum, calcium, magnesium, titanium, and oxygen. All other elements are present in the rocks, but none are known to have been concentrated into useful ores. Conspicuously absent, except for trace concentrations, are the biologically important elements--carbon, hydrogen, and nitrogen. Water is absent unless caches exist in polar cold traps. The lunar soils contain usable amounts of iron-nickel alloy derived from meteorite impacts. The minerals ilmenite ($FeO.TiO_2$), olivine [$(Mg,Fe)_2SiO_4$], and feldspar ($CaO.Al_2O_3.2SiO_2$) can be found as rocks or separated from the soils. During the two-week lunar day, the constant sunshine provides an excellent energy source.

Lunar rock or soil can be melted to make glass, as fibers, slabs, tubes, and rods. Sintering can produce lunar bricks and ceramic products. Iron metal can be melted and cast or converted to shaped forms by powder metallurgy. Possible uses for these products would be habitat construction, electrical power transmission, and shielding materials.

Iron, aluminum, titanium, silicon, and oxygen can be freed from lunar materials by using chemical and electrochemical conversion techniques. Oxygen may become an early economical product from the Moon. Silicon can be used in photovoltaics or to "stretch" the effectiveness of imported hydrogen by producing silane, SiH_4, a combustible fuel. Silicon and titanium can be alloyed with iron to make steel. More sophisticated separation and containment processes would be required to extract hydrogen, nitrogen, and carbon, which exist on the Moon only in small quantities.

Facilities and Equipment

Beyond the obvious needs for habitation and transportation, the first production modules are the key facilities of an industrially oriented lunar base. Earliest production modules should be designed to operate with a high degree of reliability, taking account of all reasonable contingencies. We expect the modules will operate mainly in an automated mode. However, they will be managed to some extent and should be capable of repair, adjustment, and perhaps modification, so that base personnel can meet most contingencies.

In addition to production modules, equipment for modifying the site and preparing the habitat is essential. For example, two front-end loaders could be used to carve trenches for cut-and-cover placement of habitat modules. The loaders would also be needed to construct a landing pad, slightly below grade to reduce the effects of flying dust disturbed by engine blasts. Then they would be used in setting up production modules, providing rock and soil feedstocks, and removing tailings and products.

It is important that personnel at the lunar base be able to operate essential equipment easily. They should also have adequate freedom and time to do repairs and to develop variations on operating techniques. Therefore, the lunar base should have appropriate laboratories, shops, and maintenance bays.

Considerable attention must be given to environmental control. Dust must be kept out of machinery as well as buildings where people live. Industrial activities can affect scientific experiments and observations, especially those requiring clear viewing, seismological quiet, or preservation of soil stratigraphy. Reasonable personnel comfort must be attained if tours of duty are months long and personnel are to think and function effectively.

Another key component of the industrially oriented lunar base is electrical power. So far, solar voltaic, nuclear, and fuel-cell power sources have received the greatest attention. Megawatt quantities will be needed for steady product output. For some purposes, simple devices based on expansion and condensation of refrigerants between sunny and shaded areas may prove useful.

Site Selection

The most straightforward location for the first industrial lunar base is one of the Apollo sites, because we know them best. Should the processing facility require ilmenite concentrates, a soil rich in titanium at a location near basalt would be needed (Apollo 11 or 17 site). If feldspar were most needed, a highland site would be preferred (Apollo 16 or Apollo 17).

Discovery of water in the polar regions could greatly influence the eventual choice of industrial processes and products and perhaps the location of the base. The potential value of any lunar polar water is modified by our lack of information about the poles, the more complex transportation required, and the possible need to operate in the dark of permanently shadowed craters. Transport of water-rich material to a more nearly equatorial site might be preferable.

Forward-Looking Developments

Substantial research must be done immediately to develop suitable industrial techniques before the end of this century. Research needs include a better knowledge of lunar materials and detailed testing of proposed procedures for separating them into feedstocks and processing them into useful forms. Because we need economically competitive processes, many possible ideas and more than one generation of a single idea must be tested before processes are chosen for pilot-scale development. This work and analogous research in related areas will require at least a decade and must be done by the mid 1990s. A crash program to condense this research into a shorter time scale is likely to be neither cost effective nor as successful as a longer effort that allows ideas to mature and be tested. Serious planning for a lunar base early in the next century should be under way now.

Toward Self-Sufficiency

Initially, all activities in space will be heavily dependent on products from the Earth. As these activities increase, there must be greater reliance on materials from nonterrestrial low-gravity sources. The rate at which these materials become available will affect the costs and, therefore, the rate of growth of opportunities in space. This, in turn, depends on the development of a proper lunar base infrastructure.

Even in the long term, self-sufficiency in space should not mean the production of all items needed there. For any reasonable future, it will be easier to make small, sophisticated, and lightweight items on Earth. The first decades of the industrial lunar base should focus on industry and agriculture for use in space rather than on absolute self-sufficiency.

A Lunar Base as a Stage in Human Development

A lunar base has been viewed in the previous two sections in terms of what its direct, practical return might be, first in increasing scientific knowledge about the solar system, the universe, the nature of life, and other fields, and second in the use of lunar resources to support a growing space economy. The lunar base also can serve as the next significant step, beyond the permanent Space Station in Earth orbit, toward humanity's permanent and self-sustaining habitation of space. Near-term achievements associated with a lunar base would include

- The first practical experience toward adapting to life on another planetary body.
- The first demonstration of humanity's ability to alter the environment of space through innovative use of native materials.
- Development of the infrastructure to tap natural resources of space to create profitable enterprises.
- Demonstrating much of the technology and possibly acquiring some of the resources necessary to support the subsequent human exploration of Mars.
- Advancing the physical and life sciences to create new views of our universe and to help us understand the space environment.

The advance of human capability beyond LEO requires a new stage in the technology development, emphasizing systems that will enable people to live and work comfortably and securely in the new environments. The issues of self-sufficiency are wide ranging, from closed life-support (environment maintenance) systems (CELSSs) to the governance of future space settlements. We choose to address here only a few of the concerns in moving toward self-sufficient human settlements away from the Earth.

Human Functions and Relationships

Whether the primary focus of the lunar base is human habitation of the Moon or the scientific and economic potential of the Moon, humans will play key roles in all stages of lunar base development. From a systems point of view, human functional capabilities include discrimination, vision, hearing, touch, gross and discrete manipulation, technological education and training, and analytical judgment in dealing with the unexpected.

During all phases of lunar base planning, development, and operations, the integration of human functions with the capabilities of instrument, machine, and technological systems should be constantly considered. The patterns of such human-system integration must be reassessed during the evolution of the lunar base and its supporting orbital and transport components.

The need for high efficiency levels in lunar base operations, in terms of cost and manpower effectiveness, will demand high levels of human productivity. Assuring this productivity will require automated systems and intensive human-machine interaction. As the lunar base grows in size and complexity, the multitude of human activities will present increasingly complex information management requirements; these will support lunar productivity and transfer information to Earth, while the lunar base systems will become increasingly automated. The need for human control and direct involvement will remain; intensive man-computer interactions will increase as the operations progress from lunar "camps," through small permanent bases, and to larger communities. Accordingly, we stress the need for research to assure effective human-computer interactions. Further, as the technology of robotics advances, we expect that developments in this area will increase use of teleoperator and robotic devices. Therefore, careful assessment is required to determine the appropriate role of the human operators and the proper mix of humans and machines at each level of complexity of the lunar establishment.

At all stages of lunar base development, from training to establishing the initial camp, we must develop methods to ensure the essential balance of technical skills, personal characteristics, working organization, authority of lunar personnel, and relations to the national program.

An important area for near-term research is what social organizations are required at each level of complexity in an expanding lunar base. For the initial "camp," the group may well be patterned along military lines (that is, with a commander and subordinates). However, for a large, permanent community, the concept of a crew may not be viable. These societal considerations for lunar base operations need attention, and models must be developed of the transition from a command-type structure to the potentially different requirements for a larger, more diversified population.

It would be easy to lose sight of the human aspects of a lunar base program. While it is proper to consider humans as "system components" in some parts of the planning process, we must continue to recognize that a human presence on the Moon is properly a primary reason for the program.

Health and Medicine

Humans living for long periods at a lunar base will be exposed to acute and chronic environmental circumstances not experienced on Earth. Inevitable primary physical stresses will include extreme and sudden alterations of gravitational force during launch operations, in orbit, and in transit; long duration exposure to low (1/6 g) gravity on the lunar surface; prolonged exposures to harsh respiratory environments; and prolonged isolation and confinement of small groups.

The pathophysiological and pathopsychological consequences of relatively short exposures to individual stress factors are now being studied. However, the potential effects of interacting stresses and of the exceptionally prolonged exposures involved in a lunar base require research prior to and during initial stages of lunar base activity. Success of a lunar base program requires the maintenance of physiological and psychological health of lunar personnel in circumstances approaching self-sufficiency. Special research and development must encompass metabolic, nutritional, enteric, respiratory, skeletal, neuromuscular, and hematological systems, the immune mechanism, and the endocrine functions under the circumstances predictable for successive stages of lunar base evolution.

Beyond routine health maintenance and preventive medicine, provisions must be made for technical procedures, medical supplies, and equipment for diagnosis and therapy for illness and injury. Such requirements can be expected to increase with successive stages of lunar base and transport development. At all stages in this development, support mechanisms can be devised to provide technical backup (for example, detailed communications) from Earth.

Life-Support Systems

The development of life-support systems for the initial lunar "camp," the subsequent base, and finally the community with closed ecological life-support systems (CELSSs) can occur in stages. The first lunar base can be supported using Space Station life-support systems, which rely on physical/chemical regeneration of water and air and resupply of food. When the initial base is established, current research directed toward simple bioregenerative systems that will supply a portion of the required food and regenerate air and water should be at an advanced stage, and the systems should be ready for testing on the lunar surface. These systems will evolve into more complete bioregenerative systems that can support a larger lunar base with increasing independence from Earth. A complete CELSS should have been ground tested and ready for checkout in the early, permanent lunar base to give a more varied and complete food production capability. Enlargement of this system will become the basis for a self-sufficient community with a high degree of independence from Earth.

The requirement for eventual development of closed ecological life-support systems dictates that we investigate several technological and developmental areas. These include, but are not limited to,

- designing and developing devices to monitor and control the system,
- selecting appropriate plant species (including improvements resulting from plant breeding and genetic engineering),
- selecting and maintaining appropriate gas pressures and compositions,
- selecting appropriate photoperiods and light sources,
- selecting appropriate growth media and systems for nutrient delivery,

- developing microbial systems to enhance agricultural productivity and the stability of the general life-support system, and
- extracting plant nutrients from lunar materials.

The trend of development for the life-support systems will thus be from physical/chemical systems with resupply for a base camp using present technology to bioregenerative systems for a self-sufficient lunar settlement.

Some of the technical issues, such as potential effects of one-sixth gravity on plants, can be investigated in space on the Shuttle or Space Station equipped with a centrifuge. Strategies must also be developed to optimize the conservation and recycling of materials at all stages in the life-support system.

Lunar Shelter Technology

Lunar regolith ("soil") is the only raw material available for processing into materials and for fabricating structures. Because human lunar activities require shelter to execute many tasks, establishing shelters will be a first priority beyond the camp stage.

These shelters must possess workshop capability and "shirt sleeve" and "suited" environments in various combinations. Several types of shelter will be required: radiation-shielded, with and without pressurization, and solar-shaded, with and without pressurization. Shelter is required for a range of functions and must be in a corresponding range of shapes and dimensions.

If we consider the above parameters, we have good reasons for developing a concept of shelters that provide the shielding and pressurization functions separately after the camp stage, until we are self-sufficient in shelter technology. This means constructing shielding canopies from regolith materials using the materials in several ways: (a) loose regolith to cover partially sunken pressurized shelters; (b) arched or flat structural canopies made with processed regolith elements supporting loose regolith, over pressurized shelters; and (c) cooling any shelter that provides shielding and pressurization in the same envelope by using processed nonporous regolith components, sealed joints, and loose regolith cover.

Pressurized shelters, initially manufactured on Earth and assembled on the Moon, could be established under loose or processed regolith shield canopies. These structures could be either rigid enclosures of metal and plastic assembled by bolting, screwing, clipping, and taping, or soft enclosures assembled and kept in place by inflating.

EVA Activities and Systems

There will always be a requirement for extensive manned operations outside of shelters on the Moon, the Space Station, the Shuttle, and other vehicles in the overall lunar base program. Specific methods and supporting equipment (for example, suit characteristics, thermal control, mobility, manipulative aids, traction, and sensory aides) should be conceived in relation to key working circumstances and functions.

EVA systems for lunar operations should capitalize on the current technology developments for the Space Station (polar and geosynchronous) manned operations. These newer technologies are directed toward making suits easier to don and doff and making gloves more useful. However, in contrast to the case for Space Station EVA systems, the existence of low lunar gravity will actually simplify many of the strict design and operational problems imposed by zero gravity (for example, waste management, phase-change materials, and heat-transfer issues), and new designs will be necessary.

For lunar EVA systems, attention should be directed toward the possible use of "end-effectors" for manipulations, backpacks to dissipate body heat more effectively in extended lunar operations, and systems to allow *extended* (more or less continuous) stay-times in EVA activities. As mobility and complexity of operations on the Moon increase, systems may need to blend human-robot and suit-vehicle elements to maximize human productivity. Materials and manufacturing processes that incorporate protection against radiation and micrometeorites should receive more attention for use in these lunar EVA systems.

Research on lunar bases and related space operations should also include physiological research to improve the ease and speed of entry and exit of humans from space vehicles and lunar shelters. Such research could improve compartment atmospheres to prevent decompression sickness (and the requirement for subsequent therapy) and could also permit rapid use of low-pressure suits with improved mobility and manipulative capability.

TECHNOLOGY DEVELOPMENT FOR LUNAR BASES

Many of the activities proposed for a lunar base will not be carried out in the first stage. To better address priorities for research and development, we found it necessary to develop some model for the growth of lunar activity. Many alternatives are possible. A report prepared by the Johnson Space Center for presentation at this workshop described an evolutionary model with three concepts: (1) an initial scientific station, similar to an Antarctic research base, which could be temporarily or intermittently occupied and which could grow to be a permanent establishment; (2) a production facility, which could prepare material, such as liquid oxygen, for use away from the Moon and which would be highly automated, requiring only maintenance personnel or occasional visits; and (3) a research base aimed at supporting fundamental science and at understanding problems of developing a self-sufficient lunar base or colony.

For this document, we adopted a general buildup scenario that is representative enough to indicate major technology issues, but which is not detailed enough to identify many required technological developments. During the workshop, some important technology issues were identified. These are presented in Appendix D, which serves to indicate the types of problems involved in the long-term development of a lunar base program.

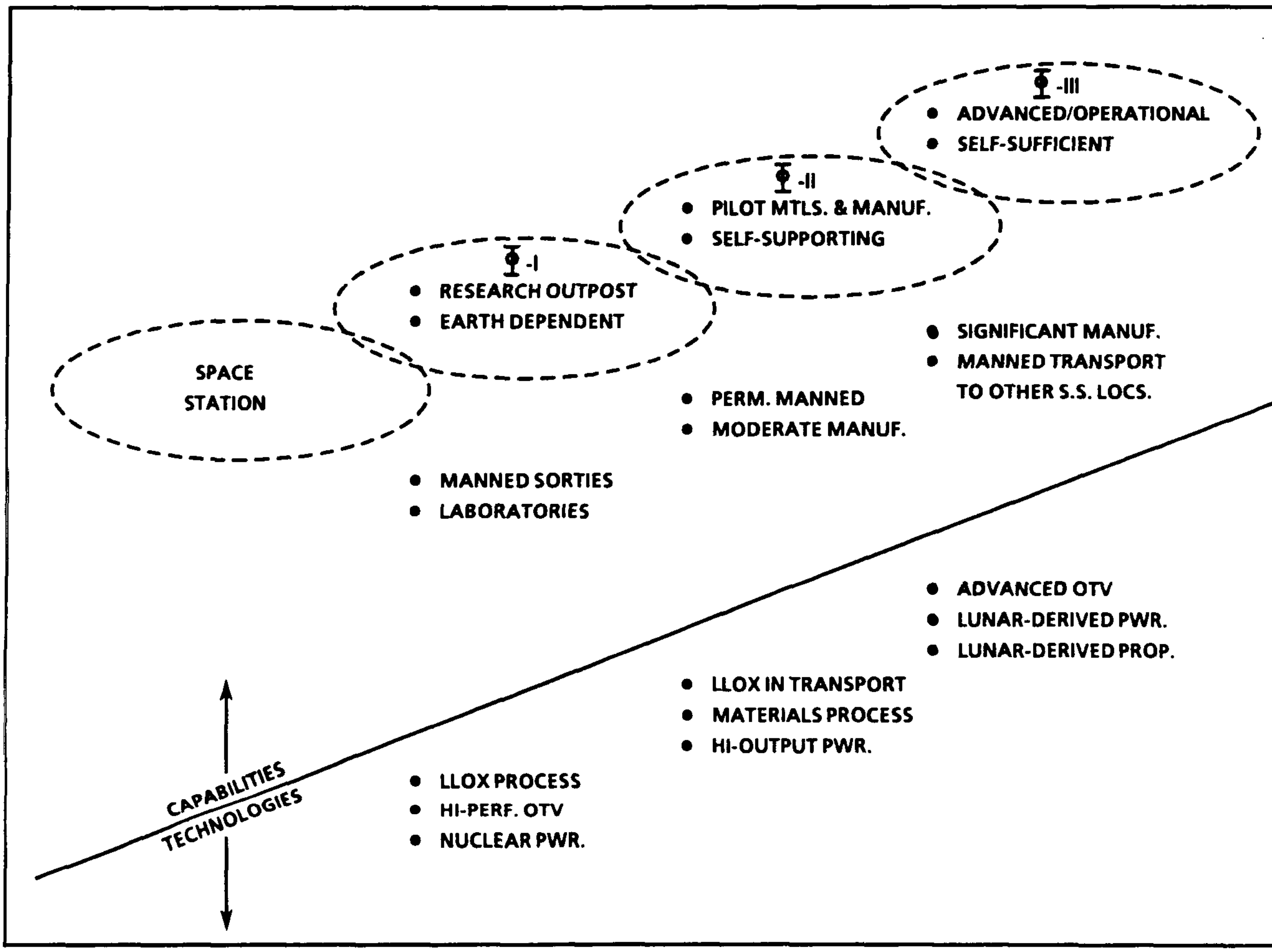
Technology as a Function of Lunar Base Developments

The evolutionary growth scenario for a lunar base, the essential capabilities associated with each growth phase, and some of the high-leverage technologies required to advance from one phase to the next are shown in the figure below.

The assumed evolutionary growth begins with a program definition phase that includes the preliminary lunar mapping and surface exploration needed for site selection. The first lunar base (Phase I) is a scientific and technological research outpost with some options for pilot plants. It is likely to be intermittently manned because of limited base capacity. The major changes between this outpost and Phase II are the introduction of a permanent manned presence and the addition of more pilot plants. Because transportation costs are the key cost driver, the ability to use lunar-derived oxygen in some parts of the transportation system is anticipated in Phase II. Phase III is a fully operational base with moderate manufacturing capability and pilot biological life-support systems. This phase quickly becomes virtually independent of the Earth as it matures into a self-sustaining base with CELSSs and significant manufacturing capability. At this stage, the Moon becomes a node in the transportation system and can support not only ready access to all of cislunar space but to other planetary space as well. The Moon can, in the advanced phases, serve as a staging and propellant supply point for manned Mars exploration, and, in the long run, serve as the departure point for a Mars base.

Earth-Moon Transportation

Current transportation costs for the Space Shuttle to deliver material into low Earth orbit



Technologies versus Phases of Development.

are about $1,000 per pound. More economical modes of transportation, such as those brought by development of automatic, large shuttle-derived launch vehicles (SDLVs), would significantly enhance our capability to support a lunar base, both during construction and in later operation. The SDLV may be a key enabling system to a lunar base--comparable with the impact of the C130 Hercules airplane upon Antarctic outpost operations.

The current projected costs of transporting materials to the lunar surface are approximately $10 to 15 thousand per pound, using existing STS technology. There is a potential reduction to $3 to 5 thousand per pound based on the development and eventual use of a shuttle-derived launch vehicle (SDLV). Even with the SDLV, two-thirds of the cost of a lunar base is in transportation to the Moon. Initial approaches to reducing this cost burden include development of a high-specific-impulse, lightweight OTV with aerobraking. This capability would be augmented to include space-storable propellants, which can be maintained in the space environment for long periods without loss or deterioration. A major cost reduction could also be produced by the use of lunar liquid oxygen (LLOX), oxygen produced on the Moon. Other efforts would concentrate on subsequent propulsion systems using totally lunar-derived materials. These technologies include chemical systems, ion or MPD electric propulsion systems using LLOX, and mass drivers.

Primary issues include (1) integration of these requirements into the current studies for the Space Station, OTV, and HLLV; (2) LLOX production processes; (3) cryogenic propellant storage and transfer; and (4) development of lunar-derived chemical propulsion systems and production processes.

Habitation

For lunar habitability, closed life-support systems make possible increased stay-times, decreased resupply, and maximum self-sufficiency. Toward that end, closed ecological life-support system (CELSS) technology should progress from mechanical and/or chemical systems of increasing sophistication towards closed-cycle, regenerable biological processing. Similarly, suit technology should, to enhance human productivity, move toward garments with greater mobility, better atmospheres, and enhanced regenerability to permit increased exposure time. The necessary addition of lunar agriculture also leads to enhanced self-sufficiency for the base.

Critical issues include the technical approaches, side effects, and implications of complete life-support system closure; the potentials of lunar agriculture and the impact of unwanted agricultural by-products; and the critical impacts of human interactions, psychology, crew makeup, health, and task assignment.

Using Lunar Resources

The concept of lunar resource utilization produces a radical change in all facets of the space program growth rate, including Earth orbital systems, planetary exploration spacecraft, and the lunar base itself. Although the initial base relies entirely upon Earth-derived technology, we consider that it would carry out research and experimentation into appropriate uses of lunar resources. The second stage of development would incorporate *in-situ* fabrication from terrestrial feedstocks. Eventually maximum use would be made of lunar feedstocks, *in-situ* processing, and fabrication of materials and structures.

A major concern is that the techniques needed for resource processing on the Moon cannot be simply modified from terrestrial activities, which are based on concentrated areas, abundance of air and water, and a high gravity field. The types and mix of resources that can be brought from Earth must be examined, in order to determine the most economic lunar approaches in light of the complexity, skills, and specialized equipment required. Another concern is that proposed processing techniques are largely untried; they are exotic and complex, and they require high temperatures or the use of special reagents.

Energy Supply (Electric/Thermal)

The past history of the space program shows clearly that a power-rich system is critical to user capability and growth flexibility. Lunar base energy supplies are perceived as moving from Space-Station-derived systems of roughly 100-kWe capacity (using both photovoltaics and the present SP-100 nuclear power system) towards multimegawatt, utility-type systems of mixed solar and nuclear sources. Systems to use and reject the large quantities of heat produced by human existence, operations, and industrial-type processing are also essential.

Critical issues include the possible effects of the lunar surface environment on high-capacity power system operation, as well as the adaptability of the SP-100 technology to the lunar environment. Other concerns include the appropriate mix and evolutionary development of complementary solar and nuclear technologies and the emphasis on lunar-derived versus Earth-supplied nuclear technology.

Human Productivity

Because the lunar vacuum environment inhibits human EVA and its effectiveness, we must capitalize on the rapidly emerging robotic technologies likely to be present in the year 2000, in order to support and make effective use of, valuable human work. Humans should serve where they best operate: that is, in first-time events; in unexpected, rare, or unusually complex tasks; and in tasks requiring judgment. Automation should be planned for tasks that are routine, boring, hazardous, or clearly definable. Teleoperations can directly substitute for human presence in many situations. Autonomous robots will emerge as intelligent human surrogates as AI technology matures. These critical technologies will be stimulated by ongoing Space Station activities, LEO teleoperators, planetary programs, and GEO platforms.

Major issues in this area include the accuracy of automation technology forecasts, limitations in the applicability of nonaerospace technology to space projects, and the economics of research and capital investment in this emerging arena. It is especially important to consider the potential tradeoffs among direct human control, artificial intelligence, and the use of dedicated, single-purpose machinery. Finally, in constructing a development program, we must consider the projected technology evolution relative to the expected needs on the lunar surface.

SYSTEMS REQUIREMENTS FOR LUNAR BASES

Previous sections have identified potential uses of the Moon and some requirements for development of necessary systems. To begin to define the manner in which such uses and programs might be achieved, we must first specify systems requirements. This is a difficult task because we are just beginning the process of identifying and setting priorities on various uses and objectives for a lunar base; thus, no single plan can be developed. However, certain elements have emerged as issues, and these can be discussed.

Transportation Systems

Developers of models for the establishment of an early lunar base have generally assumed that the first lunar habitats would be derived from Space Station modules. Such modules have nominal masses of approximately 20 tons. Therefore, we expect that it will be necessary to deliver to the lunar surface a payload of approximately that size. Currently, the United States has the capability to move such a mass to low Earth orbit (LEO), using the Space Shuttle as the delivery vehicle. However, at present, we cannot transfer payloads of that size beyond LEO.

To move payloads of significant size to the Moon, we must provide an effective Earth-Moon transportation system. Such a system could logically develop from the combined Space Station-orbital transfer vehicle model currently under study. At the Space Station, payloads from Earth would be mated with a reusable transportation system, which would be fueled for the lunar leg of the journey. *The near-term Space Station initiative will thus enable a lunar base.*

A reusable lunar lander can transfer payloads from lunar orbit to the lunar surface. Such devices alternatively can provide one-way delivery (non-reusable), thus increasing the payload for each landing. At later stages of lunar base development, a lunar orbit station, probably derived directly from the Earth-orbit Space Station, could provide the same staging function at the Moon that the Space Station will provide in Earth orbit.

Vehicles will be required to transfer people to and from the lunar surface. Vehicle size and characteristics depend on how many people will be transported and on what schedule.

Habitation

Early habitation on the Moon may use components from the Space Station. For long-term residence, habitation modules must be shielded from occasional high-energy solar radiation so Space Station modules, if they are used, must be buried. Access must be provided to the surface. Environmental control must minimize the transfer of lunar dust to the interior of the base.

The number of people to be supported at a lunar base depends on the scenario adopted. Previous studies suggested 6 to 12 as the crew size at the initial base. In a growth phase, the ability to utilize lunar materials can substantially reduce the need to bring structural materials from Earth and can provide a more rapid expansion of living and work space. However, certain key elements of controlled environment systems, particularly air-locks and interfaces, will be needed as the system expands.

Habitats must support the continued effectiveness of the personnel occupying the lunar base. Lunar base models for personnel rotation time range from 3 months to a year or more. The longer the proposed rotation period, the greater the demands of the psychological environment provided by the lunar base.

Life-Support Systems

Adequate supplies of the basic elements required for life support are essential for maintaining a lunar base. Water and oxygen recycling, carbon dioxide removal, trace gas removal, and control of trace elements are issues for long-term occupancy. Closed life-support systems (CELSSs) are discussed earlier in this document. Such systems provide the minimum need for resupply from the Earth and are probably essential for the lunar base to become a permanently inhabited facility. The production of oxygen and possibly water from lunar materials is an objective for an early base, to provide additional safety and flexibility for the life-support system.

Power

As pointed out previously, many problems can be overcome if abundant power is available. We envision 75- to 100-kWe power systems in our present Space Station concepts. A lunar base, with a variety of scientific and production activities under way, may require 1- to 10-MWe class power plants at a relatively early stage. Because the lunar day is 14 Earth days long, power must also be provided through the 14-day night, when direct solar radiation is unavailable for photovoltaic systems. At the lunar poles, locations may be found where continuous sunlight is available.

Surface Mobility and Extra-Base Activity (EBA)

Many operations at a lunar base, including scientific experiments, exploration, production facilities, equipment maintenance, and construction, require that people and machines leave the controlled environment of the lunar base and travel on the lunar surface. Special purpose vehicles will be needed for several crucial activities, beginning with the removal of shelter payloads from lander vehicles; continuing through excavating, emplacing, and covering the shelters with lunar soil; and finally providing base personnel with the ability to explore several tens of kilometers from the base. Personnel must have life-support systems that provide sufficient range, reliability, and security so that EVA becomes routine and relatively easy.

Adaptive Capabilities

One major challenge of a lunar base will be to provide the means by which humans can use their ingenuity to explore the uses of available materials and energy, thereby expanding their abilities and enriching their lives at the base. In activities as diverse as utilitarian uses of lunar materials to nurturing artistic expression, sufficient supporting equipment must be available to allow experimentation. This area is very poorly defined at present, but one possibility would be the use of melted lunar materials (glasses) in both technical and artistic activities.

Special Purpose Equipment and Facilities

There are numerous requirements, in a lunar base, for both scientific equipment and equipment for the production of useful materials from the resources of the Moon. Some areas of consideration will undoubtedly be mining machinery to move and process lunar rock and soil; furnaces and thermal systems for high-temperature processes, such as solar furnaces for melting and vaporizing lunar-derived materials; manufacturing equipment; analytical equipment for scientific laboratories; machine shops and equipment repair facilities; and special scientific apparatus--telescopes, drill rigs, and plant growth chambers.

POLICY IMPLICATIONS FOR A LUNAR BASE PROGRAM

A lunar base program has implications well beyond those of science and technology. Many political issues arise when a project of such dimensions is proposed. The establishment of a lunar base must be examined from diverse viewpoints to determine its place within national and international programs and its returns to society versus its costs.

As mentioned in the Introduction, recent changes in the United States make a Moon-base project feasible within 15 to 20 years. These changes include the development of an operational Space Shuttle, the reversal of the economic recession of the early 1980s, the targeting of space development as a high-technology investment by the private sector, the public acceptance of the federal space effort, and the President's support of a Space Station program.

These changes allow NASA planners to focus on steps beyond the Space Station, particularly those that involve human activity. The present climate provides an opportunity for the nation to adopt longer-term goals that will maintain this enthusiasm and will cause it to grow over the next decade, as we develop the technical capability to undertake such programs as a lunar base.

Costs

The interplanetary program we are advocating will require large sums of money for completion, and our recommendations are made at a time of budgetary stringency. The program, however, is a very long-term one. It is vital to understand that, subject to the appropriation process of Congress and the performance evaluation of the Executive branch, these expenditures would continue into the next century.

The cost of a lunar base is estimated as roughly comparable to the Apollo Program, which amounted to less than 0.3% of the U.S. GNP from 1962 to 1972. Since the Apollo Program began, the present U.S. GNP has more than doubled, after inflation. Furthermore, the evolutionary nature of establishing a permanent lunar base suggests a duration twice that of the Apollo Program. A lunar base program, therefore, will cost less than 0.1% of the U.S. GNP and can be supported without increasing NASA's historical percentage allocation. International cooperation may produce budgetary commitments from others, as has occurred in the Space Shuttle program.

Precedents already exist on Earth for large-scale projects comparable in magnitude to the lunar base. Private enterprise has provided more than nine billion dollars of investment in the Alaska pipeline. The U.S. government has supported the Interstate Highway System with at least forty billion dollars. The new port-city of Al Jubyl, Saudi Arabia, will cost upwards of fifty billion dollars before completion. The 1,300-mile Grand Canal of China, under contruction during two millenia, represents an even greater investment in terms of current monetary values.

The consonant problems of management and analysis of such large projects are now widely recognized as being of critical importance; leaders of government, industry, and the universities have founded special societies for the study of macro-engineering. A Space Grant College system has been proposed, based on the precedents of the Land Grant Colleges resulting from the 1862 Morrill Act and the more recent Sea Grant Colleges established to improve United States competences in oceanography and ocean engineering. Such efforts could enhance the opportunities to channel the commitment of a younger generation of Americans to large projects in space exploration and utilization.

Extraterrestrial Legal Implications

Space law as a specialized branch of international law is clearly recognized and accepted by all nations. In the course of its 25-year evolution, at least four multilateral space treaties have been promulgated and have entered into force. From these treaties, and the concomitant customary practices of nations, five fundamental principles presently undergird extraterrestrial law:

- space, including celestial bodies, is the province of humanity and should be developed for its benefit;
- space, including celestial bodies, should be free for exploration and use by all countries;
- space, including celestial bodies, is not subject to national appropriation by claims of sovereignty, by means or use or occupation, or by any other means;
- space, including celestial bodies, shall be used exclusively for peaceful purposes; and
- international law as formulated on Earth does extend to outer space and celestial bodies.

These hallmark principles supply the contemporary international legal framework for initiating, planning, and executing a lunar base program.

International law, however, is a dynamic process. It grows, matures, and adapts to changing international political conditions and legal circumstances. So, also, will it be for space law. Although national appropriation today is prohibited, one should not assume that territorial sovereignty will be legally precluded forever. Indeed, the notion of functional sovereignty appears implicitly legitimate in contemporary space law. States retain rights to exercise jurisdiction and control over their own activities in space. Similarly, no legal regime exists today for governing space development or the greater role of private enterprise in space-related activities, not the least of which is resource appropriation.

In short, contemporary international law affecting space-related activities is neither static nor necessarily permanent. Indeed, humanity's increasing activities on the Moon particularly and in outer space generally will undoubtedly generate the need for new extraterrestrial law. Only in this way will international law be able to deal more effectively with political-economic problems arising from extensive exploration of outer space and the presumed utilization of its natural resources.

Policy Alternatives

The allocation of priorities among the objectives to which a lunar base might contribute and the selection of an institutional framework for carrying out the program are both significant policy decisions. Which international framework is appropriate will depend, among other factors, on the priority goals for the undertaking. In addition, each framework offers particular political, economic, technical, and organizational advantages and disadvantages.

Among the possible institutional frameworks for a lunar base program are the following:

- One in which the United States defines, finances, and implements the program, possibly with the solicited participation of others in a United States-dominated effort.
- One structured as an international cooperative endeavor because such cooperation may be an effective means for accomplishing the program's objectives. If the program is part of a broad-scale thrust into the solar system, active participation of high-level policy makers is required. If the program is aimed primarily at the use of the Moon for scientific investigations, it could be either a coordinated effort among separate national activities or a collaborative effort under international scientific management--an international lunar laboratory established on the model of CERN, a European particle physics laboratory.
- One organized as an international consortium on the model of INTELSAT. Here stakeholders in the program would share planning, management, and potential payoffs in proportion to their involvement, but the international character of the enterprise would obviate

many of the concerns raised by unilateral national efforts.

- One organized to exemplify the benefits of close and continuing international collaboration in achieving commonly desired objectives, with the explicit purpose of providing a counter example to continuing Earth-bound conflicts.

There need be no contradiction between national and international approaches to a lunar base program. Often national interests, not only in the long term but even in the shorter range, are best advanced through international cooperation. Indeed, countries seldom enter into meaningful cooperative arrangements unless it is in their interests to do so. The national policy objectives toward which a lunar base program is aimed will be the critical determinant of the optimum mix between unilateral national efforts or various multilateral approaches; thus, there is no *a priori* way of specifying one "best" framework for a lunar base program without a set of policy discussions regarding the reasons for undertaking that program.

Relation to Near-Term NASA Programs

The Space Shuttle has recently reached operational status, and NASA is concentrating on the need to increase the number of annual flights and reduce the cost of each flight. As confidence in the system grows, more tasks will be identified that can be performed by the shuttle and its crews. Stretching stay-times, increasing the effectiveness of crew performance, and providing new capabilities for on-orbit investigation and services will remain significant elements of NASA's program for the next decade. Capabilities, such as satellite repair, demonstrated on the Solar Maximum Satellite repair mission; refueling rockets and satellites, to be demonstrated in the near future; the tethered satellite program; and others are now in the forefront. Many of these capabilities will provide the stepping stones of development to those needed for a lunar base program.

A Space Station program has received Presidential approval and has now been approved by Congress for the "new start" and first year funding. This will be a major development project. Installation of hardware in space is planned for 1992, and there will be growth in capability over the rest of the century.

There are several ways in which a lunar base program would utilize an Earth-orbit Space Station and the technology developed as part of a Space Station program. These include

- Use of the Space Station as an operational node for the transportation system to the Moon. Such support requires that the Space Station must be configured at the proper time to support lunar missions and must include capabilities to support a substantial amount of lunar traffic (perhaps 1,000,000 pounds per year). Appropriate upper stages (orbital transfer vehicles) must be available to travel between LEO and lunar orbit, and the Space Station must provide such services as refueling, inspection and maintenance, logistics, crew accommodations, and other features. If lunar base program requirements are not considered, elements of the Space Station may develop at an inappropriate pace or aspects of Space Station design may make it difficult to support lunar base activity, thus leading to additional costs to implement the lunar program.
- A lunar base program will probably use evolutionary Space Station technology for its initial habitation, power, thermal control, communications, data management, and other requirements. A space program that anticipates a lunar base following the LEO Space Station should ensure the greatest possible technical inheritance in these areas. Designs for Space Station architecture should not preclude adaptation for use of its components at a lunar base.
- The lunar base program would benefit from a lunar orbit Space Station, a facility that could be a direct descendent of the LEO Space Station.

To the extent that the Space Station development can anticipate future needs, the costs of a lunar base program can be reduced and its development concentrated on the truly unique requirements of operating on the Moon. For these reasons, it is important to consider the lunar base as the Space Station is being designed to assure that critical decisions, which could impact the later lunar base activity, are made from this broader perspective.

The technology requirements described in this report can be considered near-term program requirements for NASA. Many of these are generic technologies, requiring development in the broader context of space activities, and many of these technologies are now under study by NASA's Office of Space Flight and its Office of Aeronautics and Space Technology. For example, the SP-100 program to investigate nuclear power for space applications has direct application to lunar surface as well as to orbital operations.

One significant area that currently receives little support is that of utilization of lunar materials. This area involves research and development of long-lead-time technology; the problems are unique enough and different enough from other NASA technology programs that, for various reasons, this research area has not had a comfortable organizational home in NASA. Using lunar materials is, nevertheless, essential for a lunar base program, and a NASA commitment can now return substantial future dividends.

More fundamental engineering and scientific lunar data are needed. These data may be useful in considerations of site selection, in definition of major scientific experiments, and in identifying potentially useful resources, as well as for generally improving our understanding of the Moon. NASA's Planetary Exploration Program has defined a Lunar Geoscience Orbiter project that will address many of the next science issues for a lunar base program, with the possible exception of improved mapping imagery for lunar polar regions. This mission will be flown in the early 1990s according to current projections. Such timing could provide data for a lunar base program that is initiated in the mid 1990s. The Lunar Geoscience Orbiter program should consider the needs of subsequent lunar base activites as the mission is planned and carried out. To properly focus and guide these efforts, overall systems studies of various lunar base scenarios are needed.

Comparison with Alternative Scenarios

A lunar base program, when it is undertaken, will be initiated in a technological, scientific, political, and economic environment that will differ considerably from today's. The workshop was not able to give serious consideration to a broad range of alternative or complementary national activities that might be desirable in the mid 1990s, when the intervening developments in space activities have provided a sound basis for initiating a lunar base program. These activities include both space and terrestrial possibilities, which will have a set of priorities at that time. Some of the future opportunities in space activities were discussed at the workshop, but detail was insufficient to provide serious commentary.

The perceived cost of lunar operations is not considered a serious concern at this point. It will be the role of those who advocate a lunar base program to develop the arguments for the selection of that program as a beneficiary of public funds, both nationally and internationally. The better the planning, the lower the ultimate costs can be and the greater the benefits. Advocates of alternative scenarios for future development should also pursue their cases vigorously, so that the necessary information and education are available when decisions are made.

CONCLUSIONS AND RECOMMENDATIONS

Although detailed technical conclusions and recommendations were not drawn, some central conclusions were reached.

- Workshop attendees generally believe that a lunar base goal has a high enough potential payoff that it should be adopted by NASA in the near future. Such a lunar base will represent a major expansion of space activities, reaching into the region beyond low Earth orbit. Potential gains include new possibilities for scientific investigation, utilization of the natural resources of the Moon to benefit lunar and space operations, and development of a long-term capability for human self-sufficiency on another planet.
- To reduce the risk that near-term decisions will be made that result in future difficulties or additional unnecessary costs to a lunar base program, we must consider near-term development issues, such as the Space Station and the orbital transfer vehicle technology, in light of their potential application to a lunar base program.
- The lunar base program is envisioned as being less of a technological challenge and less expensive annually than Apollo was. However, it is complex enough that serious attention should be given soon to a study and research program aimed at understanding the technical, scientific, political, and economic consequences of a lunar base initiative. Such a program would include continued scientific investigations of the Moon as well as the technologies identified above.
- Several key technological developments, currently under consideration in near-term NASA programs, are required to make possible a lunar base program at reasonable costs. These include a permanent manned capability (i.e., a Space Station) in low-Earth orbit to provide a necessary node in the Earth-Moon transportation system; a reusable upper stage (orbital transfer vehicle) based on cryogenic hydrogen/oxygen propellants, for Earth-Moon transportation; expansion of space power generation capability to 100 kW and beyond; and long-term habitation experience in the space environment.
- Several key developments are necessary for an economical lunar base program that contains the proper ingredients for growth. These include technology to obtain from lunar resources the materials needed for life support, propulsion, construction, and other manufactured products for use in space or on the Moon; lunar base-specific vehicles and tools, such as lunar landers, lunar surface vehicles, mining and other special-purpose machinery; and closed ecological life-support systems (CELSSs).
- We should establish a mechanism for continuing the dialogue on issues of the lunar base development. Fifty people were assembled for the workshop, and they became enthusiastic as the workshop progressed. It is important to broaden the group of people who can interact in the development of the concepts and plans that will be necessary. The Symposium planned for October 1984 will lead us in that direction, but specific plans for continued coordination and communication should be established soon as a part of the study activity identified above.

APPENDICES

APPENDIX A
SETTLEMENT OF THE MOON AND VENTURES BEYOND

The "white paper" is a concise statement of the recommendations of the Lunar Base Workshop. This independent document, which suggests how a lunar base fits into our nation's future, is reproduced on the opposite page. Names of workshop attendees who concurred with the white paper are listed on p. 30.

SETTLEMENT OF THE MOON AND VENTURES BEYOND

by

The Lunar Base Working Group

We scientists, engineers, industrialists, and scholars of law and history were convened at Los Alamos by NASA in the last week of April 1984, to deliberate matters concerning the establishment of a permanently manned base on the Moon's surface. Early in our discussions we realized that a fundamental reason for building a lunar base is to obtain the benefits of further exploration. As in the past, the associated scientific and technological discoveries will improve the quality of life on Earth. But in a broader sense, space exploration stimulates an even greater response.

The exploration of space touches the most profound elements of human nature. It excites our spirit of adventure and challenges us to achieve our full potential. It confronts us with the awesome beauty of creation. We are convinced that exploration beyond the Earth is a natural function of a space-faring nation.

We also are persuaded that space exploration should be coupled with continuous human residence on other celestial bodies, such as the Moon and Mars. In this way, we can learn to utilize the ocean of space better. The enterprise will increase our scientific knowledge, expand our commercial capabilities, sharpen our technological skills, and open our access to additional resources. The scale and nature of the undertaking will create new opportunities for global cooperation and peaceful competition and will fire the next generation's enthusiasm to extend its space exploration beyond the limits of our own.

Furthermore, space activities will be more efficient if supplies are freed from complete dependence on the Earth's resources. The Moon is a promising source of extraterrestrial supplies. We know enough about lunar resources to foresee the production of oxygen, power, fuel, building materials, and metals--all of which can be useful to space endeavors on the Moon, in near-Earth orbits, and elsewhere in the solar system. Thus a lunar base represents an investment in other space programs, and an early commitment to this objective will influence the character of some space projects currently being planned.

We therefore recommend that this nation advance scientific exploration, expand opportunities for commerce, and prepare for the permanent habitation of other planets by adopting the goal of returning to the moon. Specifically, we propose that a series of investigations be initiated now by appropriate institutions to consider permanent facilities on the Moon as the next step beyond the low Earth-orbit Space Station. Our national civilian space program should incorporate this goal and encourage international participation.

In 1972, we withdrew from the Moon. Restoring our capability to visit the lunar surface presents no insurmountable technical obstacles, and establishing a permanent base is well within our reach. In this venture from the Earth, we can develop opportunities to serve the Earth. We can begin a new age in which horizons of mankind are expanded and aspirations of future generations are fulfilled. We can continue to explore the heavens and, for the first time, live there.

The Following Workshop Attendees Concurred With The White Paper

Mickey Arthur
Mark Bitensky
Henry W. Brandhorst, Jr.
James D. Burke
W. David Carrier III
Paul Cloutier
Paul Coleman
Frank Davidson
Hubert Davis
Daniel Deudney
Michael B. Duke
Carl Erdman
Bevan French
Herbert N. Friedlander
Charles L. Gould
William K. Hartmann
Larry A. Haskin
Philip Helmke
Albert R. Hibbs
Eric M. Jones
Christopher Joyner
Paul W. Keaton
Harold P. Klein
Christian Lambertsen
Peter Land
Robert W. Langhans
Raymond S. Leonard
John M. Logsdon
Robert H. Manka
Harold Masursky
Wendell W. Mendell
Stewart Nozette
Barney Roberts
Stanley Sadin
Harrison H. Schmitt
Wallace O. Sellers
Harlan Smith
Page Smith
David W. Strangway
G. Jeffrey Taylor
Mead Treadwell
Arthur B. C. Walker, Jr.
Gerald Wasserburg
Stanley Weiss

APPENDIX B
ABBREVIATIONS, ACRONYMS, AND NOTES

AI	artificial intelligence
AXAF	advanced x-ray astronomy facility
CELSS	closed ecological life-support system
CERN	Centre Européen pour la Recherche Nucléaire
EBA	extra-base activity
EUV	extreme ultraviolet
EVA	extravehicular activity
g	unit of gravitational acceleration at the surface of the Earth
GEO	geosynchronous earth orbit
HLLV	heavy-lift launch vehicle
IGPP	Institute of Geophysics and Planetary Physics
INTELSAT	International Telecommunications Satellite Consortium. A communications satellite organization and the satellites it launches
IRAS	infrared astronomical satellite
JSC	Johnson Space Center
kW	kilowatts
LEO	low Earth orbit
LLO	low lunar orbit
LLOX	lunar (-created) liquid oxygen
LOX	liquid oxygen, used in propulsion systems
MPD	magneto-plasmadynamic thrust system
Mtls	materials
MW	megawatts
NASA	National Aeronautics and Space Administration
OTV	orbital transfer vehicle, orbit to orbit
PV	photovoltaic
regolith	the layer of pulverized rock material resting on bedrock that constitutes the surface of the Moon (sometimes referred to as lunar soil)
RFC	regenerative fuel cell
SDLV	shuttle-derived launch vehicle
SETI	Search for Extraterrestrial Intelligence
SP-100	joint NASA-DOE-DoD 100-kW space nuclear power development project
ST	space telescope
STS	space transportation system

APPENDIX C
WORKSHOP ORGANIZATION AND STRUCTURE

The Lunar Base Workshop was sponsored by the National Aeronautics and Space Administration and hosted by the Los Alamos branch of the Institute of Geophysics and Planetary Physics (IGPP), University of California. IGPP was responsible for logistics, including travel arrangements for participants, local travel, accommodations, clerical services, and refreshments during working group meetings. The workshop was held in the J. Robert Oppenheimer Study Center, which provided a central meeting room and several adjacent areas where working group participants could meet formally or informally to discuss topical areas.

The agenda for the meeting is shown in the form of a diagram in Figure C-1. Relatively short (2 to 2-1/2 hours) interspersed plenary and working group sessions allowed participants to hear summaries of the other working groups. Five working groups were established: Scientific Uses of the Moon, Industrial Uses of the Moon, Self-Sufficiency (which became human considerations in general), Technology Implications, and Societal Implications. Each afternoon the participants joined in plenary session to hear progress reports by working group chairmen. On the second morning and on subsequent mornings, the "keeper of the outline" reported on the development of documentation of material that would become a final report, using a straw-man outline prepared in advance of the workshop and modifying it during the discussions. Through these summarizing activities, discussion was encouraged and directed towards filling gaps in the final report. A summary report was delivered by working group leaders during the final session on April 27.

During the workshop, working groups developed informal documentation of their discussions through the preparation of working papers. In preparation for the final report, each working group was asked to prepare a six-page summary of its work. These summaries were assembled into a draft final report, which formed the basis for this report. At the conclusion of the workshop, all working papers were assembled and distributed to workshop attendees.

Clerical support for the workshop was provided by staff of the Los Alamos Technical Associates, Inc. (LATA), who provided typed reports in near-real time during the workshop, taking material delivered as late as 11:00 P.M. and providing the typed version for meetings the next morning. LATA was also responsible for producing this final workshop report.

Workshop attendees are listed in Appendix E.

Day	8–9	9–10		10–11		12–1 PM	1–3		3–4		5–6	6–7	7–9
APRIL 23 MONDAY	ARRIVAL AT LOS ALAMOS											RECEPTION (PUNCH AND COLD CUTS)	PLENARY • STUDY OUTLINE • MEET THE 5 GROUP LEADERS
APRIL 24 TUESDAY	PLENARY WELCOME TO LOS ALAMOS	PLENARY NASA STUDY PRESENTED	COFFEE, DANISH	WORKING GROUP MEETINGS		PLENARY WORKING LUNCH DISCUSSION, STRATEGIES, QUESTIONS	WORKING GROUPS	REFRESHMENTS	PLENARY GROUP LEADERS' REPORTS	EVENING PLANS DEVELOPED	DINNER (UNSTRUCTURED, LOCAL RESTAURANT LIST SUPPLIED)		UNSTRUCTURED, INDIVIDUAL AND GROUP EFFORTS
APRIL 25 WEDNESDAY	PLENARY KEEPER OF THE OUTLINE REPORT	WORKING GROUPS	COFFEE, DANISH	WORKING GROUPS		LUNCH (INDIVIDUALS)	WORKING GROUPS	REFRESHMENTS	PLENARY GROUP LEADERS' REPORTS	LAMPF TOUR		DINNER (LOCAL RESTAURANTS)	UNSTRUCTURED, INDIVIDUAL AND GROUP EFFORTS
APRIL 26 THURSDAY	PLENARY KEEPER OF THE OUTLINE REPORT	WORKING GROUPS	COFFEE, DANISH	WORKING GROUPS		LUNCH (INDIVIDUALS)	WORKING GROUPS	REFRESHMENTS	PLENARY GROUP LEADERS' REPORTS			DIRECTOR'S RECEPTION	PLENARY WORKING DINNER
APRIL 27 FRIDAY	SUMMARY OF THE STUDY	PANEL DISCUSSION	COFFEE, DANISH	CONCLUSIONS AND RECOMENDATIONS		(ALL FRIDAY MORNING MEETINGS PLENARY) RETURN TRAVEL							

Fig. C-1. Workshop Agenda.

APPENDIX D
TECHNOLOGY ISSUES AND OPPORTUNITIES

Table D-I restates a growth scenario similar to that adopted in the earlier discussion of technology development for lunar bases. Listed are generic technologies that could be required at each phase or that would characterize the phase. Examples of more specific technology research projects in lunar industrialization, habitat construction, biomedical research, and Earth-Moon transportation systems are given in Tables D-II through D-V. Other areas of study are also important.

TABLE D-I

TECHNOLOGICAL REQUIREMENTS OF LUNAR BASE SYSTEM

Technology	Phase I	Phase II	Phase III	Phase IV
Electric/Thermal	100-kW Sp-100 Deriv. Multi-100-kW Thermal	mW Nuclear mmW Thermal Solar Heating/Dynamic	Utility	
Propulsion	OTU-Derived Ferry	Lunar LOX OTV	Lunar-Derived Propellant, Electric Propulsion	Electric Propulsion
Lunar Surface Transport				
Local	Apollo-Derived Manned/Teleoperated Rover	PV/RFC-Powered, Increased Range and Capacity, Expert Systems, Materiel	Specialized Vehicles, High Automation	
Remote	Descent from Lunar Orbit	Electric Propulsion	Manned Electric Propulsion	
Habitability				
Life Sciences	Basic Experiments	Limited Independence	Maximum Independence	
Medicine				
Agriculture				
Life-Support Systems				
Habitat	Mechanical Waste Processing	Chemical Processing	Biological	CELSS
EVA	Space Station Suit Tech.	Limited Reprocessing	Closed-Cycle Extended Duration	
Human/Machine/ Autonomous Systems	Direct Human Interaction and Telepresence	Expert System Operation	Smart Robotics for Routine Operations	
Structures/Mtls/Process				
Equipment	Earth-Fabricated Mtls Deployment, Erection	Fabrication from Terrestrial Feedstock	Lunar Feedstock	
Shelters	Regolith Cover, Construction Mtls Development	Building Mtls Fabrication/Construction	Sophisticated Mtls and Techniques	
Lunar Environment and Interactions	Environmental Measurement and Characterization	Expanded Exposure of Components, Initial Design Criteria	Design Criteria	

TABLE D-II

TECHNOLOGICAL REQUIREMENTS OR PROBLEMS OF LUNAR INDUSTRIALIZATION

Requirement	Use
Front-end loader systems	Excavating lunar soil for emplacement of habitats, mining soil
Mining equipment	Efficient excavation of rocks and soil
Mineral separation techniques	Concentration of useful fractions of lunar soil
Thermal processing apparatus	Heat lunar rocks and soil to melting temperature for casting or smelting
Solar concentrators	Collection of solar radiation for heating process materials
Dust control technology	Maintenance of clean, reliable industrial operations
Equipment maintenance facility	Repair and maintenance of heavy equipment
Chemical processing technology	Extraction of useful elements from lunar rocks and soil
Volatile extraction processes	Separating small amounts of rare volatile species from large amounts of lunar soil
Biological processing	Conversion of lunar raw materials into refined products

TABLE D-III

TECHNOLOGICAL REQUIREMENTS OR PROJECTS FOR HABITAT CONSTRUCTION

Requirement/Project	Construction Use
Thermal processing	Sintering, molding, scaling to create structural materials
Bonding agents for lunar soil	Cementitious materials, such as portland cement and double-mix epoxies, used with lunar soil for structures
Degradation of shelter materials	Radiation/vacuum exposure studies of structural materials, such as Kevlar, composites, adhesives
Thermal properties of shelter materials	Thermal expansion/contraction of structural materials in day/night thermal cycling
Shapes and sizes of components for compression arch assembly	Interlocking joints, inflatable formworks
Shapes and sizes of components for prestressed field assembly	Joints, steel, or fiberglass prestressing tendons, inflatable jacks for shelter construction
Pneumatic pressurized envelopes	For large range of pressurized chamber shapes and sizes
Base/community layout	Efficient plans for initial base and expansion
Influence of transportation	Trade studies, depending on type of transportation system adopted
Influence of solar orientation	Thermal and glare control of habitat and structures
Trenching methods	For sinking linear structures
Airlock/valve design	Separation of pressurized/vacuum space

TABLE D-IV

TECHNOLOGICAL REQUIREMENTS OR PROJECTS OF BIOMEDICAL RESEARCH

Requirement/Project	Biomedical Research
Human performance/response studies	Evaluate capabilities and problems of long-term residence at 1/6 g, lunar radiation environment, transitions from 0 to 1/6 g, long-term isolation
Life-support systems (regenerable)	Regenerate water, oxygen; remove carbon dioxide, for large habitats
Closed ecological life-support systems	
Construct plant growth chambers	Use lunar materials to reduce import costs
Extract life-support elements	Reduce costs of makeup/resupply
Study systems dealing with plant growth in 14-day lunar cycle	Optimize performance in lunar environment
Selecting/breeding plants for CELSS	Optimize productivity of lunar system
Optimize production efficiency of CELSS plants	Reduce needed size of lunar farming activity
Study role of microorganisms in CELSS	Develop multilevel organic system
Study chemical cycles in system	Optimize performance, stability of CELSS
Study rates of processes of various CELSSs	Optimize CELSS performance
Synthesize proteins abiogenically	Increase flexibility of CELSS
Effects of exposure on human function	Optimize human performance to constant environment of lunar base
Study outgassing/trace atmospheric constituent studies	Possible long-term poisoning
Microbiological environment	Response of humans to presence or absence of certain microorganisms
Dermatology	Effects of humidity, microorganisms on skin conditioning
Develop health maintenance facility	Provide health care for residents

TABLE D-V

TECHNOLOGICAL PROBLEMS AND PROJECTS OF EARTH-MOON TRANSPORTATION SYSTEMS

Problems/Projects	Transportation Systems
Definition of space-based, resuable orbit-transfer vehicle systems	Lowest cost Earth-orbit/lunar-orbit transportation (manned and unmanned may be quite different)
Systems to minimize volatile losses in cryogenic propulsion	Unknown volatile losses create large uncertainty in systems studies
Aerobrake design, mass required, reuse, derivation from lunar materials	Key to improving Moon-Earth performance
Recovery of OTV by on-board propulsion or orbital maneuvering vehicle	Technical performance and operational consideration for Space Station
Design of cryogenic engines, oxidizer/fuel ratio, specific impulse thrust/mass, lifetimes	Important in our understanding benefit of lunar oxygen
Vehicle mass fraction/scaling laws	Optimize OTV systems
Vehicle staging strategies	Optimize OTV systems
Development of lunar lander systems	Transport material and people to and from lunar surface
Earth-launch capability to support payload lunar base project	May require larger delivery than can be supplied readily by Space Shuttle
Adequacy of Space Shuttle fleet and optimization to transport personnel to low Earth orbit	Provide routine personnel transfer to lunar base
Development of advanced space propulsion capabilities, such as ion drive, nuclear electric, mass drivers	Minimize transportation costs to and from Moon

APPENDIX E
WORKSHOP ATTENDEES AND AFFILIATIONS

Mr. Joseph Alexander
New Executive Office Building
Room 5026
Science and Technology Policy
17th and Pennsylvania Avenue
Washington, DC 20500

Mr. Mickey Arthur
Environmental & Health Science
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201

Dr. Mark Bitensky
LS-DO, MS M881
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. Henry W. Brandhorst, Jr.
Mail Stop 302-1
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Mr. James D. Burke
Mail Stop 180-703F
Jet Propulsion Laboratory
4800 Oak Groves Dr.
Pasadena, CA 91109

Dr. W. David Carrier III
P.O. Box 5467
Bromwell and Carrier Inc.
202 Lake Miriam Drive
Lakeland, FL 33807

Dr. Paul Cloutier
Department of Space Technology
Space Technology Building
6100 Main Street
Rice University
Houston, TX 77098

Dr. Paul Coleman
ESS-DO, MS D446
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. Frank Davidson
E40-294
Massachusetts Institute of
Technology
Cambridge, MA 02139

Mr. Hubert Davis
Suite 125
Eagle Engineering
17629 El Camino Real
Houston, TX 77058

Mr. Daniel Deudney
Consultant
123 4th Street, S.E.
Washington, DC 20003

Dr. Michael B. Duke
Mail Code SN
NASA Johnson Space Center
Houston, TX 77058

Dr. Carl Erdman
Nuclear Engineering Department
Texas A&M University
College Station, TX 77843

Dr. Bevan French
Code EL 4
NASA Headquarters
Washington, DC 20546

Dr. Herbert N. Friedlander
Box 32
Monsanto Research Corp.-Mound
Miamisburg, OH 45342

Mr. Charles L. Gould
Shuttle Orbiter Division, D/704
Rockwell International Corp. 12214
Lakewood Blvd.
Downey, CA 90241

Dr. William K. Hartmann
Planetary Science Institute
2030 E. Speedway
Tucson, AZ 85719

Dr. Larry A. Haskin
Earth and Planetary Sciences
Washington University
Box 1169
St. Louis, MO 63130

Dr. Philip Helmke
Department of Soil Science
University of Wisconsin
Madison, WI 53706

Dr. Albert R. Hibbs
180-701
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Dr. Eric M. Jones
ESS-5, MS F665
Los Alamos National Laboratory
Box 1663
Los Alamos, NM 87545

Dr. Christopher Joyner
Department of Political Science
George Washington University
Washington, DC 20052

Dr. Paul W. Keaton
Physics Division, MS D434
Los Alamos National Laboratory
Box 1663
Los Alamos, NM 87545

Dr. Harold P. Klein
MS 200-7
NASA Ames Research Center
Moffett Field, CA 94035

Dr. Christian Lambertsen
Institute for Environmental Medicine
University of Pennsylvania
14 Medical Laboratories, G2
Philadelphia, PA 19104

Professor Peter Land
College of Architecture, Planning, and Design
Illinois Institute of Technlogy
Chicago, IL 60616

Dr. Robert W. Langhans
Department of Floriculture
Cornell University
20 Plant Science Building
Ithaca, NY 14853

Mr. Raymond S. Leonard
BDM Corporation
1801 Randolph Road
Albuquerque, NM 87106

Dr. John M. Logsdon
Science Policy Program
George Washington University
Washington, DC 20052

Dr. Robert H. Manka
Associateship Office
National Research Council
2101 Constitution Ave.
Washington, DC 20418

Dr. Hans Mark
Code AD
NASA Headquarters
Washington, DC 20546

Dr. Harold Masursky
Astrogeological StudiesU.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001

Dr. Wendell W. Mendell
Mail Code SN3
NASA Johnson Space Center
Houston, TX 77058

Dr. Stewart Nozette
California Space Institute
University of California
A-021, UCSD
La Jolla, CA 92093

Dr. Barney M. Oliver
Hewlett-Packard Company
1501 Page Mill Road
Palo Alto, CA 94304

Mr. Lewis L. Peach, Jr
Mail Code AD
NASA Headquarters
Washington, DC 20546

Mr. Barney Roberts
Mail Code ET-4
NASA Johnson Space Center
Houston, TX 77058

Mr. Stanley Sadin
Mail Code RS-5
NASA Headquarters
Washington, DC 20546

Dr. Harrison H. Schmitt
Consultant/Los Alamos National Laboratory
P.O. Box 8261
Albuquerque, NM 87198

Mr. Wallace O. Sellers
Diversification, Joint Ventures
Merrill Lynch and Co., Inc.
One Liberty Plaza, 165 Broadway
New York, NY 10080

Dr. Harlan Smith
Director
MacDonald Observatory
University of Texas
Austin, TX 78712

Dr. Page Smith
Consultant
235 Pine Flat Road
Santa Cruz, CA 95060

Dr. David W. Strangway
President
University of Toronto
Simcoe Hall
Toronto, Ontario, Canada M5S1A1

Dr. G. Jeffrey Taylor
Institute of Meteorites
University of New Mexico
Albuquerque, NM 87131

Mr. Mead Treadwell
Alaska Yukon-Pacific Corp.
P.O. Box 101700
Anchorage, AK 99510

Mr. Jesco von Puttkamer
Code MP
NASA Headquarters
Washington, DC 20546

Dr. Arthur B. C. Walker, Jr.
CSSA, ERL 310
Stanford University
Via Crespi
Stanford, CA 94305

Dr. Gerald Wasserburg
Geology and Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Dr. Stanley Weiss
Department 03-10
Lockheed Corporation
P.O. Box 551
Burbank, CA 91520

☆U.S. GOVERNMENT PRINTING OFFICE: 1984-776-026/4148